Chapter 2 The Sun

A Introduction

The sun is a modest sized star, located at the edge of the milky way galaxy. It is important to us as a source of energy. More particularly, the sun is a source of light and radiation (photons), and charged particles. We need to understand the normal behavior of the "quiet" sun, and the nature of the variations in the sun's behavior. The radiative output of the sun determines the behavior of the earth's neutral atmosphere. A more subtle, but important effect of the UV radiation from the sun is the formation of the ionosphere. Variations in the sun's UV output affect the ionosphere, and hence communications. The particle output from the sun (the solar wind) results in the region of trapped plasmas around the earth, the magnetosphere. Variations in the solar wind result in magnetic storms, which dramatically affect satellites at geosynchronous orbit.

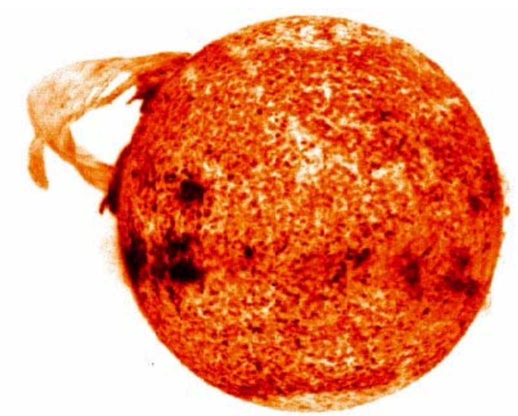


Figure 2.1 This photograph of the sun was taken using the extreme ultraviolet radiation from ionized helium, at 304 Angstrom. It was taken on December 19, 1973 using the NRL Solar Physics Branch's SO82A Spectroheliograph onboard the Skylab ATM. Note that the image here is a negative, to enhance visibility - the small black regions are bright in He II.

B A few facts about the quiet sun

Solar Radius $R_{\odot}$ = 6.96 x 10^5 km = 109 $R_{\oplus}$ which means that the volume of the sun is about 1.3 million earth volumes. ($R_{\oplus}$ is the radius of the earth)

Distance from earth to sun: Average 1.5 x 10^8 km which is 215 $R_{\odot}$. Earth moves in elliptic orbit with perihelion distance of 1.47 x 10^8 km and aphelion distance of 1.52 x 10^8 km.. Period = 365.256 earth days.

1 Astronomical Unit = 1 AU = 1.49598 x 10^8 km ~ the distance from the earth to the sun

Solar Mass $M_{\odot}$ = 1.989 x 10^{30} kg giving an average density of 1.4 x 10^3 kg/m^3 or 1.4 times density of water at ordinary temp. and pressure.

Composition: 70% hydrogen, 28% helium, 2% other (by mass). Total of 62 elements have been identified.

Overall magnetic field of 100 - 300 μT. Localized B fields can be up to 100 times these values.

Estimated Age of Sun ~ 5 x 10^9 years, Life expectancy 10 - 15 $\times 10^9$ yrs. (If nothing unexpected comes up)

Electromagnetic Power radiated 3.86 x 10^{26} W (total). This gives for power/m^2 at 1 AU: 1370 $\pm$4 W/m^2. This quantity is called the solar constant.

Spectral Distribution: 10^{-8}% RF, 52% IR, 41% Visible, 7% Near UV, 0.1% Far UV and X-Rays.

Solar Wind Emission: 10^9 kg/sec total from solar surface, mostly protons & electrons.

We have already encountered the solar spectrum in chapter 1, in Figure 1.7. There it was shown over a wide range of wavelengths (from the near UV to the far IR) the sun's spectrum as observed in space closely agrees with a blackbody at about 5800 K. The peak of the distribution curve lies near the center of the visible wavelength region. The "effective" temperature, as defined by the Stefan-Boltzmann law ($R = \sigma T^4$) , is 5800 K. The shape of the curve is better described by a black-body curve for an object at 6000 K. The discrepancy is due to variations in the temperature within the photosphere, and limb effects. (See Kenneth Phillips, *Guide to the Sun*, Cambridge Press, 1992, pages 83-84; Cambridge Encyclopedia of Astronomy, pages 131-132).

Superimposed on this black-body radiation curve it is found that there are narrow absorption bands termed Fraunhofer lines, which result primarily from absorption in the solar atmosphere. From them, we can diagnose the composition and temperature profile of the solar atmosphere. In addition, there are a wide variety of effects in the solar atmosphere which produce non-thermal radiation signatures.

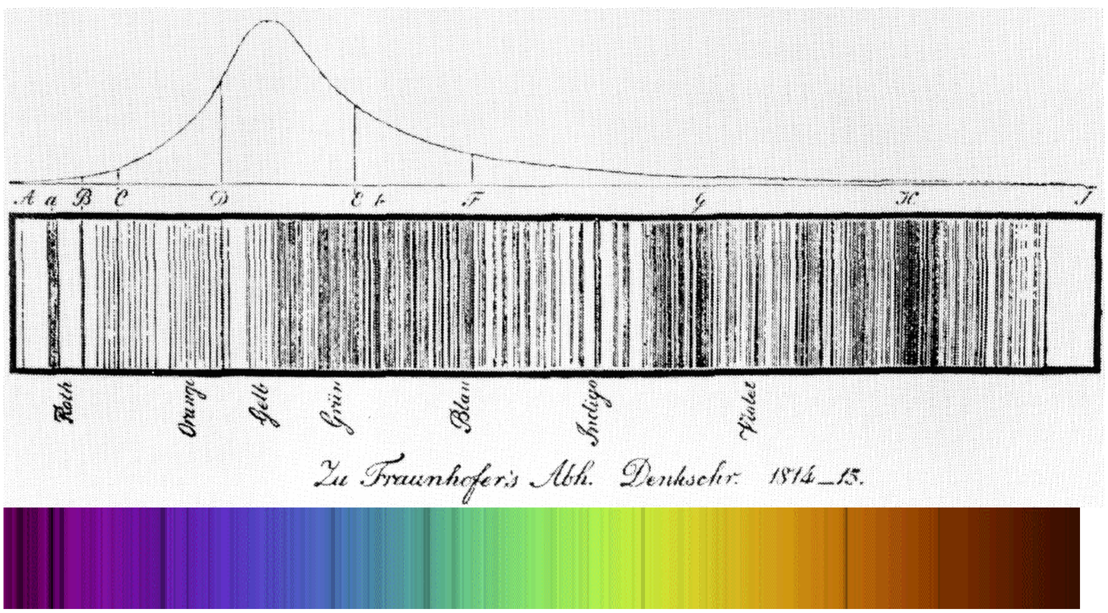


Figure 2.2 Fraunhofer spectrum of the sun. Top figure from: Phillips, Guide to the Sun A similar figure is in Sun and Earth, Friedman, page 15, 1986, and Introduction to Physics, Jay Pasachoff and Marc Kutner, WW Norton and Company, NY, 1981, plate 17. The figure in Pasachoff and Kutner is estimated to come from 1814. Bottom figure: Institut National des Sciences de l'Univers / Observatoire de Paris; BASS 2000 - BAse Solaire Sol 2000 - Antenne meudonnaise; http://mesola.obspm.fr/form_spectre.html

C The Structure of the Sun

As can be seen in Figure 2.3 we can divide the interior of the sun into several concentric regions and discuss each region in terms of its contribution to the energy transport from the core to the "surface" and beyond. The core of the sun extends to 0.2 $R_\odot$ and is the region in which fusion occurs. Hydrogen is converted into helium in the core, according to processes described in a later section. Surrounding the core is a rather massive region extending to approx. 0.8 $R_\odot$ in which radiative transport dominates. In this radiative transport region (0.2 $R_\odot < r <$ 0.8 $R_\odot$) there is relatively little change in temperature and hence not much mass motion of the plasma. The energy leaving the core is mostly in the form of high energy (~ MeV) photons. As these photons work their way outward they are absorbed and reemitted many times, each time at a somewhat lower energy. This process is sometimes referred to as radiative diffusion and consists of a large number of discrete steps in a "random walk" pattern. As a result of these multiple interactions the average photon energy is gradually decreased from γ rays to x rays to ultraviolet and eventually down to the visible light range.

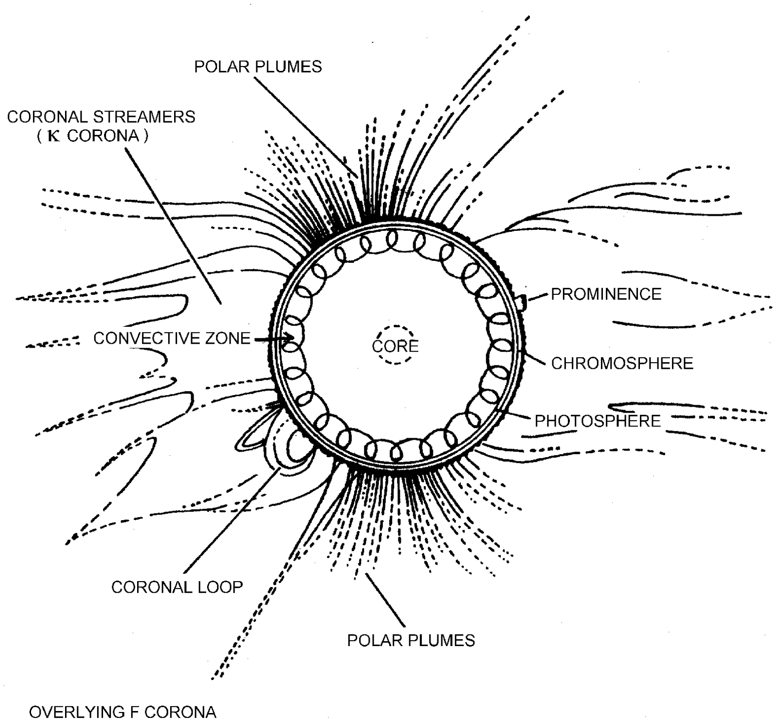


Figure 2.3: STRUCTURE OF THE SUN and the corona is summarized in this cross-sectional diagram. Energy from thermonuclear reactions in the core makes its way gradually to the sun's exterior layers. Most of the visible light received on the earth comes from the photosphere. Just under the photosphere is the convective zone. Shock waves from the convective zone carry energy up into the chromosphere and the corona. The temperature of the sun is at a minimum in the photosphere and lower chromosphere; the shock waves cause the temperature to rise through the upper chromosphere and the corona until it reaches some two million degrees Kelvin in the corona. From the corona the solar wind expands into interplanetary space. The visible corona has three major components. The first is the K corona: light scattered by the electrons in the gas surrounding the sun. The second is the F corona: light scattered by the interplanetary dust between the sun and the earth. The radiation of the third component is emitted by highly ionized atoms near the sun.

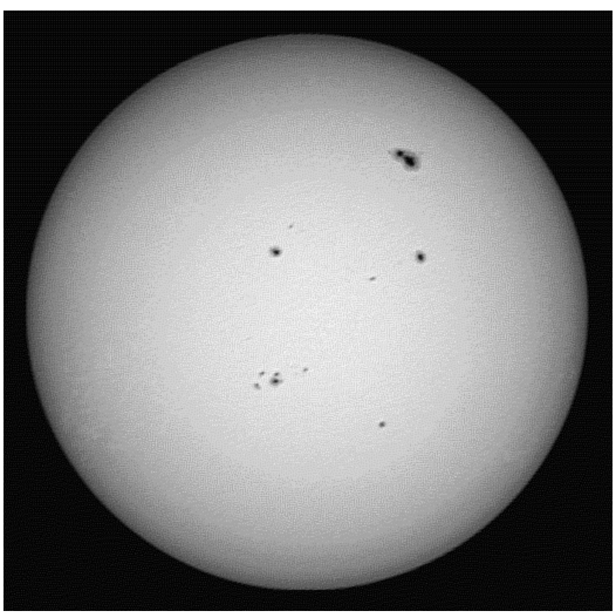
From: Scientific American, October 1973, p 69, The Solar Corona, by Jay N. Pasachoff

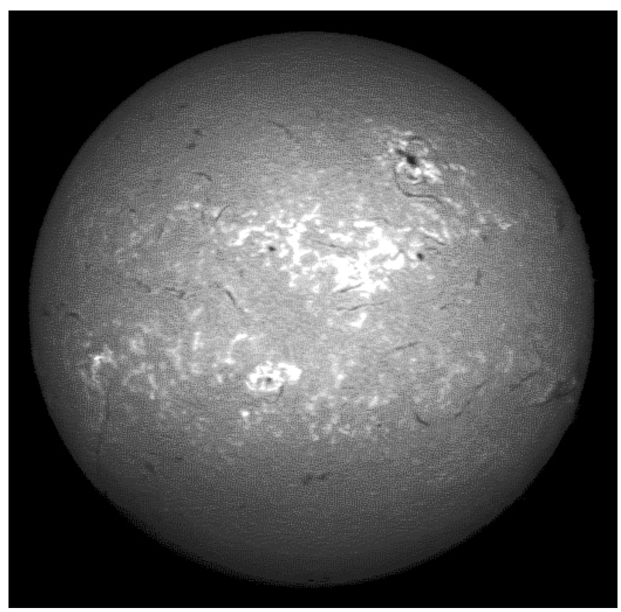
In the outer 'convective' region, transport of energy is via motion of the plasma, in a turbulent process which still shows a surprisingly well defined structure, defined by granular cells which are visible at the visible surface of the sun, termed the photosphere. At the surface, a great deal of structure can be seen, with features such as sunspots, plages, pores, and granulation. Immediately above the photosphere is region of cooler plasma, extending upwards some 10,000 km, termed the chromosphere. The solar temperature reaches a minimum of about 4,700 K at the lower boundary of this region.

Extending outward from the surface into the chromosphere (and beyond) are prominences and flares, the active processes associated with magnetic activity. Above the chromosphere is the corona, normally only visible during a total eclipse of the sun. Here the solar atmosphere increases in temperature to 1-2 million degrees.

The highly luminous surface of the sun is called the "photosphere". The photosphere is the sharp disc as observed with the eye or a small telescope. In white light, the edge of the sun, or "limb" appears as a sharp boundary. This is typically taken as giving the diameter of the sun, 1.391 x 10^6 km. Practically all of the mass of the sun is contained within this boundary. The white light image below (Figure 2.4a) shows the light emitted from that surface.

The photosphere is only ~ 500 km thick. Below the photosphere, the gas is opaque; above the photosphere, the gas is transparent. Most of the emission is from H^- (hydrogen with an extra electron). The H^- emission provides the continuum characterized by us as white light, as imaged in Figure 2.4a. (It is not an accident that there is such a sharp edge – the gradual drop in temperature and density reaches a point where radiation can escape – that escape then allows for a further very rapid cooling of the plasmas, allowing for the increasingly effective escape of the emitted radiation.)





a) White Light - photosphere

b) H α (6563 Å) - Chromosphere

Figure 2.4 Solar images from Big Bear Solar Observatory (BBSO), acquired on 13 May 1991.

Measurements over more limited wavelength ranges, at specific wavelengths, allow us to image the sun at different altitudes above the visible surface. Figure 2.4b shows one such observation, the so-called "H-alpha" measurement at 656.3 nanometer (6563 Angstroms or Å). This is one of the Balmer series transitions illustrated in Figures 1.2 and 1.5. The image primarily shows the effects of absorption by neutral hydrogen above the photosphere, a process which is largely localized in regions which are 1200-1800 km above the visible surface of the sun (e.g. in the chromosphere). (The Hα transitions are associated with temperatures of about 6000 K.) Above active regions on the Sun's surface (such as those found around sunspots), the chromosphere is heated, and the H-alpha intensity is higher (plage regions). Narrow dark 'filaments' are also observed, as talked about below.

When we observe the surface of the sun at high magnification, it reveals a mottled texture termed "granulation". Gradations in this structure exist, but the smallest granules consist of bright patches of light about 1000 km across, with a dark border. These granules have a lifetime of 5 - 15 minutes, and represent an important indication of the turbulent convective motion which is present just below the visible surface of the sun. Figure 2.5 shows an image of this fine scale structure. Doppler shift measurements show that the bright center of the cells is moving upwards. The center regions are typically 100 - 500 K hotter than the edges, where the gas descends. Vertical gas velocities are on the order of 2 - 3 km/s. They are imbedded in larger scale structures which have been dubbed 'super-granulation' cells. These have a characteristic size of 30,000 km, and a nominal lifetime of 20 hours. These granulation cells will prove important as an element in the formation of the solar wind, as described in the next chapter.

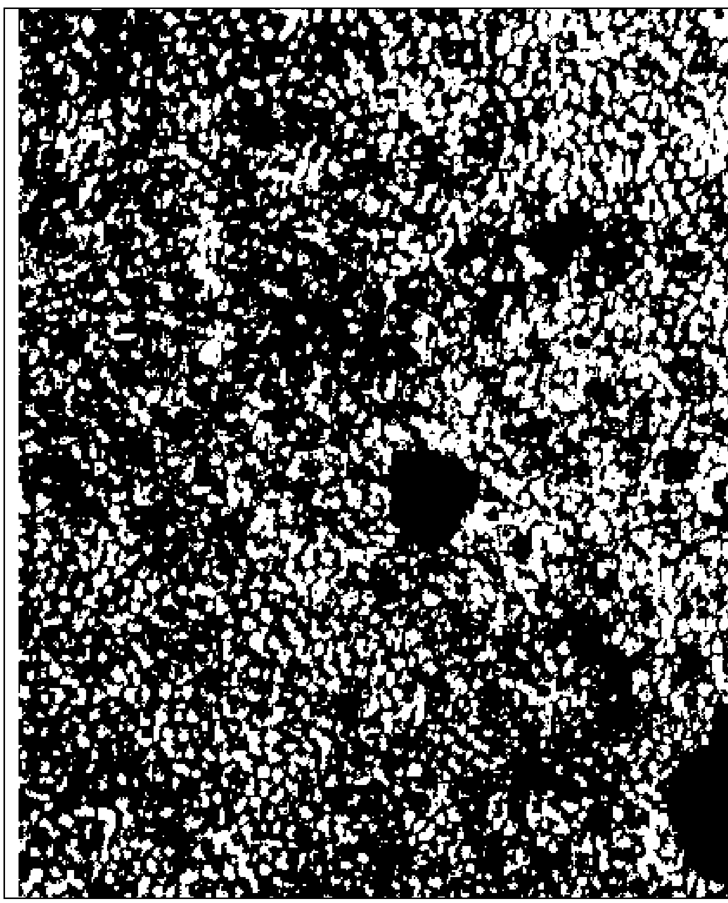


Figure 2.5a Solar granulation, pores, and small spots, July 5, 1885 (Janssen, 1896), 1mm = 0.5". (This may be the best photograph of solar granulation in existence. Janssen wrote about it: "obtenue sans aucune intervention de la main humaine.")
Taken from: The Sun, edited by Gerard P. Kuiper, 1953, Chapter 6, Solar Activity, by K. O. Kiepenheuer, p 341.

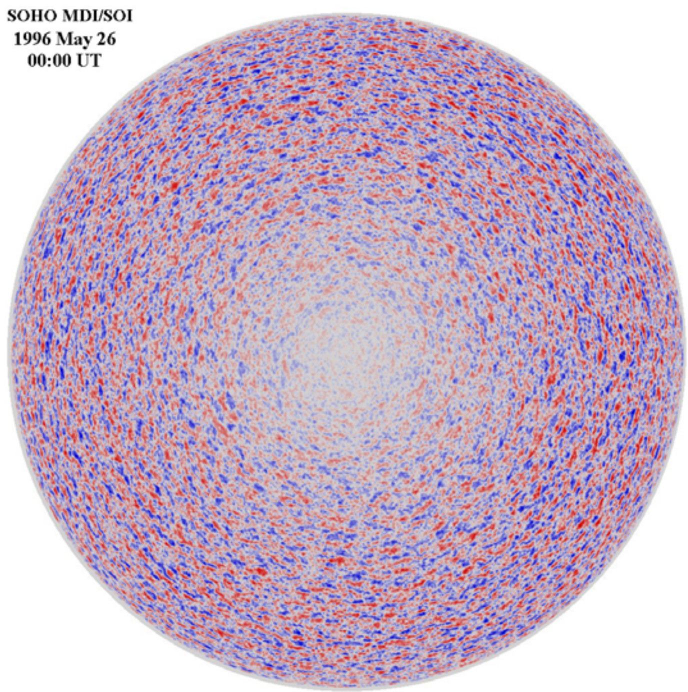


Figure 2.5 b
Supergranules are much larger versions of granules (about 35,000 km across). They are best seen in measurements of the "Doppler shift" where light from material moving toward us is shifted to the blue while light from material moving away from us is shifted to the red. These features also cover the entire Sun and the pattern is contually evolving. Individual supergranules last for a day or two and have flow speeds of about 0.5 km/s (1000 mph). The fluid flows observed in supergranules carry magnetic field bundles to the edges of the cells where they produce the chromospheric network. http://science.nasa.gov/ssl/pad/solar/feature1.htm

Figure 2.6 shows some of the consequences of the granulation structure. Note that the spicules (the 'burning prairie' of the chromosphere) occur at the boundaries 'super-granulation' cells. Note that spicules have a characteristic size of about 1000 km across, and have a lifetime of about 4 minutes. Very recent work (1999) indicates that there is an important concentration of magnetic flux in such regions, and significant upward plasma flow at the boundaries of the chromospheric network.

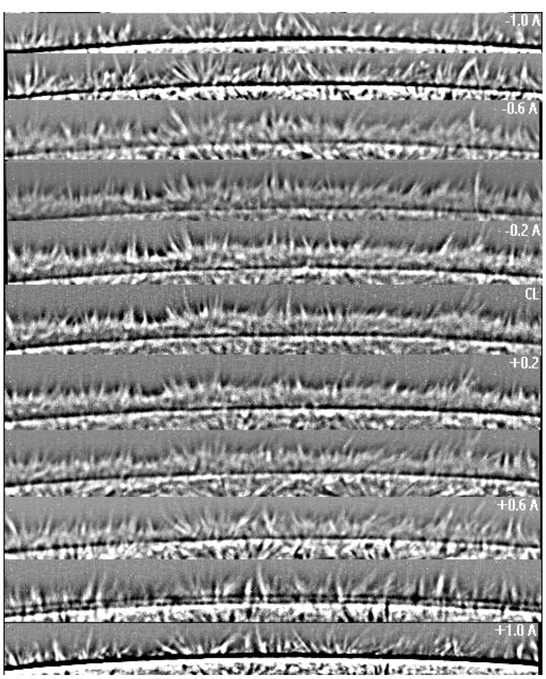


Figure 2.6a. (top) The limb of the Sun at different wavelengths within the Hydrogen-alpha spectral line are shown. Images taken from 1 Angstrom blue-ward to 1 Angstrom red-ward of the line center. Some of the spicules (jets) extend above a height of 7000 km. The images have been processed with a high pass filter. Image from Big Bear Solar Observatory - http://sundog.caltech.edu/daily/image.html. See also, Our Sun, Menzel, page 164.

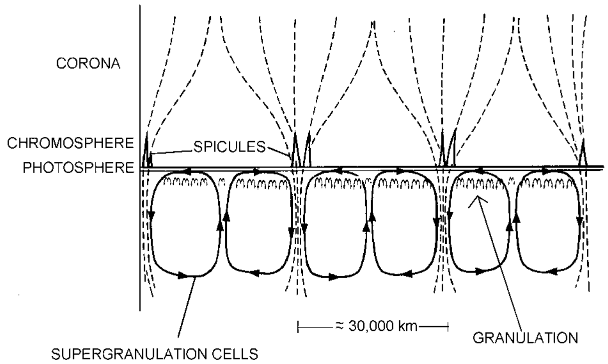


Figure 2.6b Structure at the solar surface. The flow of ionized gas from the center to edge in (super-) granulation cells carries magnetic fields to the cell boundaries, and a network of enhanced field results. Spicule location coincides with this network. (Einar Tandberg-Hansen, figure 3.2, 1967). This larger scale (granulation) structure is visible in images at 3933 Å (Ca II K image), and is termed the chromospheric network. The upward/downward motion is visible in 'spectro-heliograms', or Doppler images. The Sun, Our Star, Robert Noyes, pages 134-138.

D Solar Atmosphere

Below the photosphere the solar gas is opaque. This opacity is primarily due to a small concentration of negative hydrogen ions in the region immediately below the photosphere. These negative ions act as continuous absorbers over a great range of wavelengths, absorbing most of the intense radiation from deeper layers in the sun. The energy is reradiated into the relatively transparent gases above the photosphere and hence into space. Because the opaque gas composing the photosphere absorbs and reradiates approximately as a black body, the photosphere emits an essentially continuous spectrum. Superimposed on this continuum are a large number of dark or absorption lines (Fraunhofer lines) due to atoms of heavier elements both in and above the photosphere. This absorption spectrum is the source of most information on the abundance of the various elements in the sun and the physical state of the solar atmosphere. All the natural chemical elements known on earth probably exist in the sun, but with radically different relative abundances. Figure 2.7 shows the variation of temperature in a standard model of the solar atmosphere.

As we proceed outward from the base of the photosphere the temperature drops to a minimum of about 4700 K at an altitude of 500 km (see Figure 2.7). However beyond that point it begins to rise again as we enter the chromosphere which is a layer several thousand kilometers thick consisting of transparent glowing gas. The chromosphere is a thin, pinkish colored region when observed during eclipses. The solar atmosphere at these levels is diagnosed by observations of Ca II (3934 Å, 10,00 K) and He I at 10830 Å (50-200,000 K), as shown in Figure 2.8.

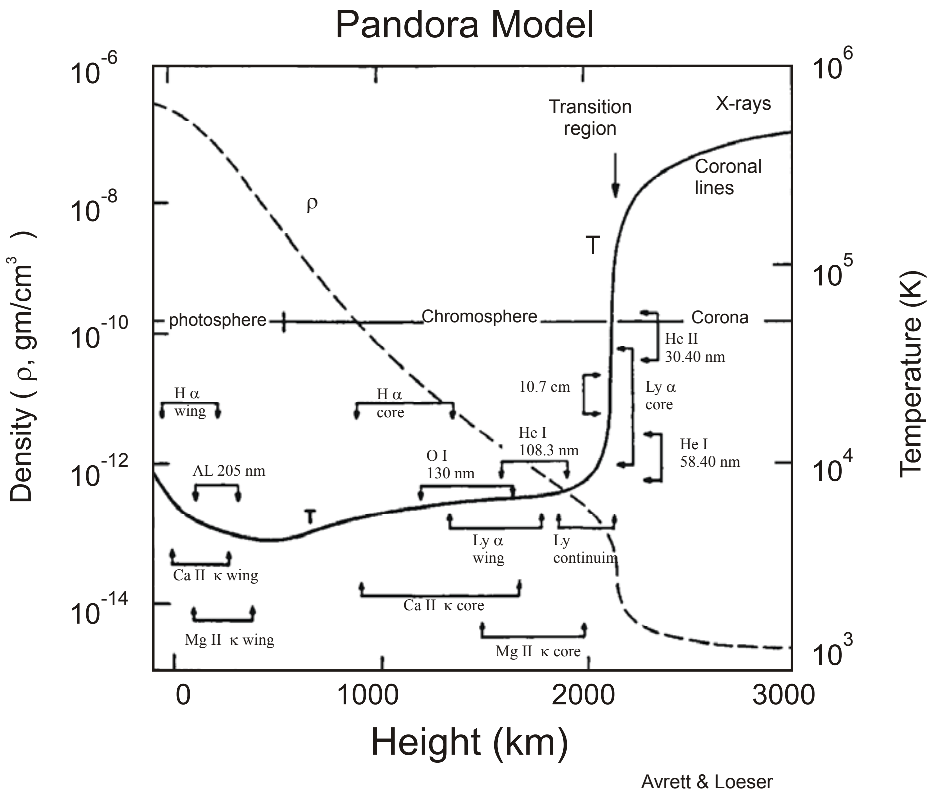
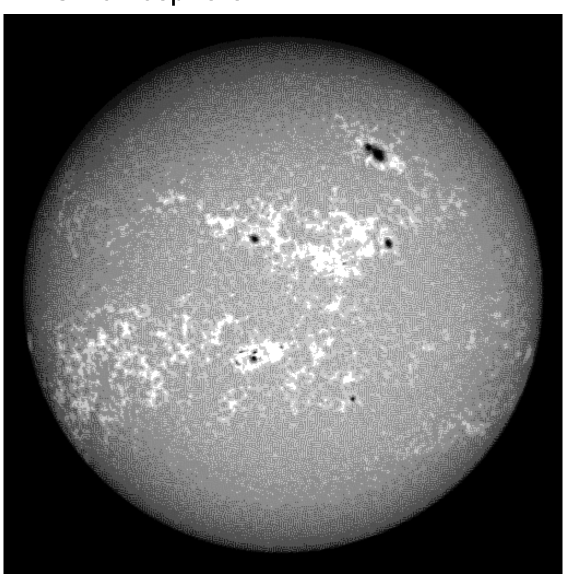


Figure 2.7 Temperature and density in the solar atmosphere versus height. The calculated position of the formation of several Fraunhofer lines are also shown. (From Avrett E.H. & Loeser R., 1992, 7 Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, ASP Conference Series, 26, Eds. Giampapa M. & Bookbinder J.

1 Chromosphere



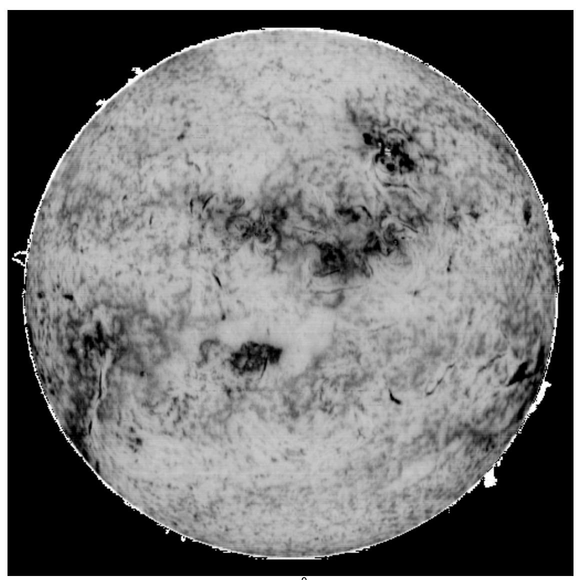


Figure 2.8a. Ca II; 3934 Å; 10,000 K Figure 2.8b He I; 10830 Å; 50-200,000 K

The CaII image is from Big Bear Solar Observatory (BBS0). The He I image is from NSO/Kitt Peak. Images acquired on 13 May 1991. Compare to Figure 2.4.

The chromosphere is illustrated here in a pair of images – one from the deep blue line at 3934 Å, the other an infrared image of light which is absorbed by a netural helium region. The Ca II K line is a strong spectral line associated with once-ionized Calcium. It has a wavelength of 393.4 nm (billionths of a meter, in the blue part of the spectrum) and absorbs about 98 percent of the light at its central wavelength. In this spectral line you view layers of up to 2000 km above the visible surface of the Sun. The center of this spectral line is very sensitive to the presence of magnetic fields in the material. If a magnetic field is present, then the absorption is less, i.e. more light is transmitted. Moderately strong magnetic fields shows up bright in images taken in this spectral line, but strong magnetic fields (such as in sunspots) don't. Typical Ca K images show brightness along the edges of cells (called supergranules) and in certain isolated areas (called plage) which, when enough magnetic field is present, are associated with sunspots and are then called active regions.

Prominences are readily seen at the limb. The bright ring at the limb is the portion of the chromosphere brighter than the sky intensity threshhold. This figure basically reflects regions where the excited helium atoms absorb radiation from below. For contrast, the SOHO satellite routinely images the sun at 304 Å, showing radiated light from He II.

The chromospheric network is a web-like pattern most easily seen in the emissions of the red line of hydrogen (H-alpha) and the ultraviolet line of calcium (Ca II K - from calcium atoms with one electron removed). The network outlines the supergranule cells and is due to the presence of bundles of magnetic field lines that are concentrated there by the fluid motions in the supergranules. (http://science.nasa.gov/ssl/pad/solar/feature2.htm#Network)

2 Transition Region

At increasing altitudes, one observes the transition region, then the corona. The transition region is illustrated in Figure 2.8b above, and Figure 2.9, an image taken by SOHO at 977.02 Å, which is a Carbon III line. The transition region is a thin (a few hundred km) and very irregular layer of the Sun's atmosphere that separates the hot corona from the much cooler chromosphere. Heat flows down from the corona into the chromosphere and in the process produces this thin region where the temperature changes rapidly from 1,000,000ºC (1,800,000ºF) down to about 20,000ºC (40,000ºF). Hydrogen is ionized (stripped of its electron) at these temperatures and is therefore difficult to see. Instead of hydrogen, the light emitted by the transition region is dominated by such ions as C IV, O IV, and Si IV (carbon, oxygen, and silicon each with three electrons stripped off). These ions emit light in the ultraviolet region of the solar spectrum that is only accessible from space.

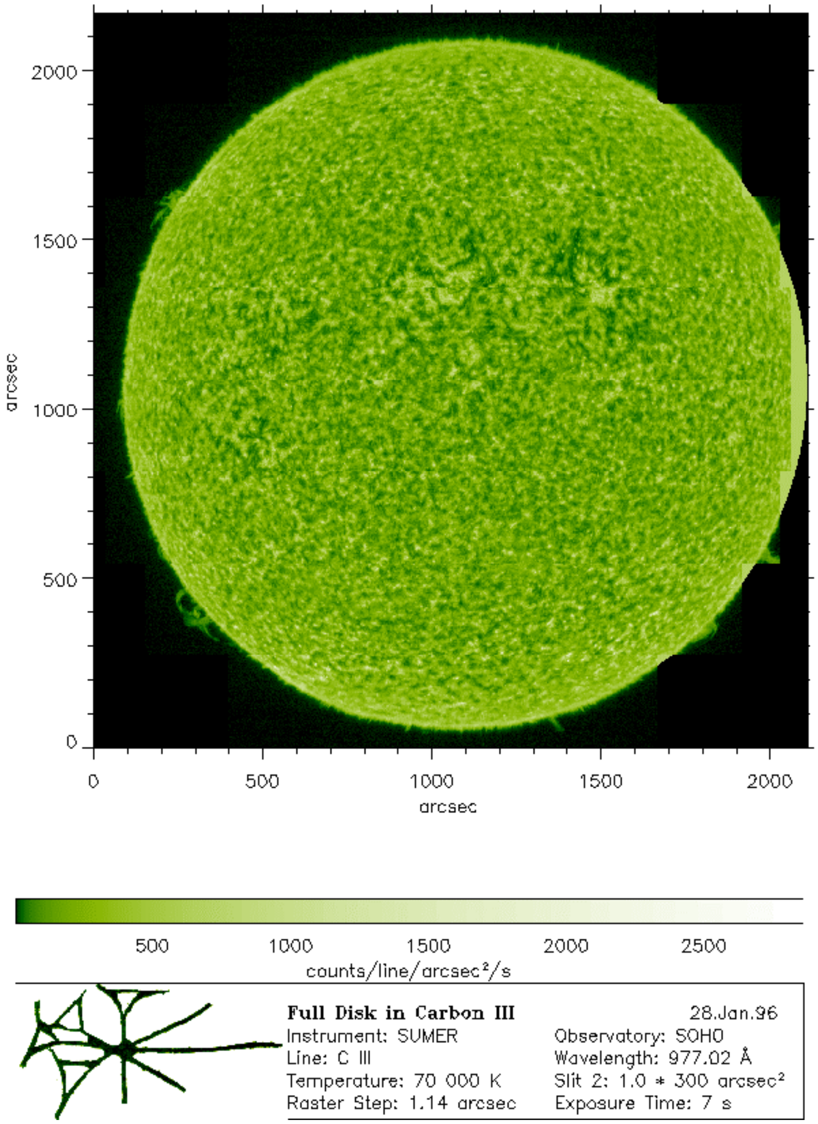


Figure 2.9 The Sun observed by SUMER on 2 February 1996 in the emission line of C III lines at 977.020, formed in the transition region at a temperature of about 70 000 K. The image is shown in bins of 4x4 pixels, one pixel being approx. 1 arcsec. The patchy pattern is the chromospheric network, with individual cells being of the size of about 30 000 km. Also note some prominences over the limb. This image was the first full Sun scan of SUMER.
http://sohowww.nascom.nasa.gov/

3 The Corona

At the interface between the atmosphere and the corona (which is the outer "atmosphere" of the sun) the temperature shoots up to 1 - 2 X 10^6 K and remains at this value throughout the corona. Figure 2.10 shows an image in Lyman-α. Extreme ultraviolet (EUV) and x-ray images such as these reveal the heating that occurs above magnetically active regions. Several mechanisms (Acoustic Shock Waves, Hydrodynamic Waves, etc.) have been proposed to explain this unexpected increase in temperature, but none of these theories is completely satisfactory at this time.

The high temperature of the coronal plasma (~100 eV) would normally produce an extremely bright region. However, because of the low density of the coronal plasma ($\leq 10^5$ particles/cm^3), it is largely transparent and is only visible in white light during a total eclipse of the sun. The visible light is primarily continuum radiation from the sun, scattered by coronal electrons. Emissions from the corona itself are mainly in the x-ray and radio bands. The corona extends out several solar radii. Beyond this point, further evaporation of the sun's atmosphere produces the solar wind. Figure 2.10 illustrates the solar corona as seen during an eclipse from earth.

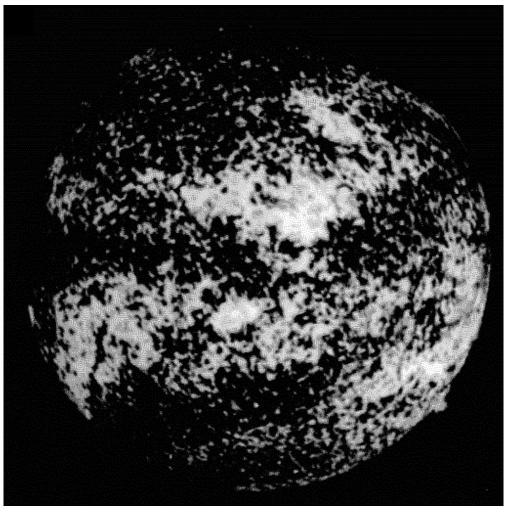


Figure 2.10a. MSSTA image in H-Lyman-α; 1216 Å; 20,000 K

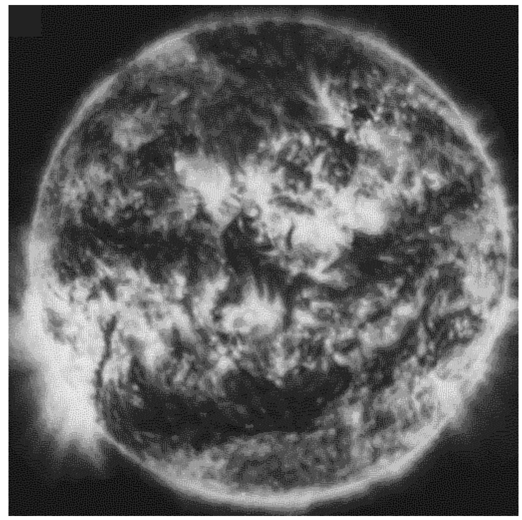


Figure 2.10b. MSSTA image in Fe XIV; 211 Å; 1,800,000 K; 13 May 1991

A set of high quality x-ray images was acquired by Richard Hoover (NASA/MSFC) and Art Walker (Stanford) on 13 May 1991, with the Multi-Spectral Solar Telescope Array (MSSTA). (Hoover, R. B., A. B. C. Walker, J. Lindbloom, M Allen, R. O'Neal, C. DeForest, T. W. Barbee, Solar Observations with the Multi-spectral Solar Telescope Array, SPIE Proceedings Volume 1546, Multilayer and Grazing Incidence X-ray/EUV Optics, page 175, 1991.) The Lyman-α image from that experiment is shown here.

The upper atmosphere of the sun can be observed at other times (that is, not during eclipse) by specially equipped ground observatores, rocket experiments, and satellites. This is generally done in the extreme ultraviolet and in x-rays. An x-ray image associated with emission from excited iron ions is shown here from the MSSTA experiment. Note that Fe XIV is iron ionized thirteen times - the source of the (relatively) famous 5303 Angstrom coronal 'green' line that so puzzled solar astronomers - they could not determine what the element was, and for a while ascribed the spectral measurements (seen during solar eclipses) to the element 'coronium' (discovered by Young and Harkness during an eclipse in 1869; Phillips, Guide to the Sun, page 23).

(The eclipse of 1869 produced several coronal lines in the visible region, which could not be attributed to any element known on earth. They were attributed to a new element, 'coronium'.The brightest lines were the green line (530.3nm) and the red line (637.4nm), with a few dozen fainter lines also discovered. The actual source of these was finally explained in 1939 as due to forbidden transitions in highly ionized iron (Fe XIV and Fe X respectively). The high temperatures necessary to create these ionization states, and the low densities to ensure the forbidden transition from the metastable states, provided further evidence of the extraordinary conditions in the corona.)

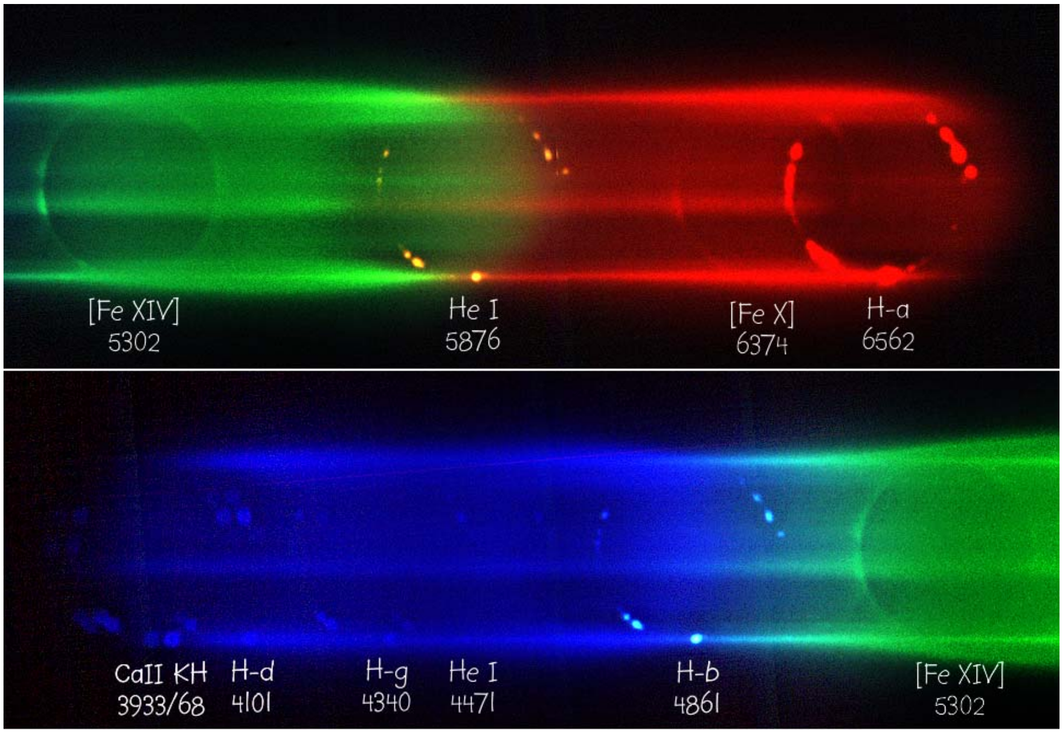
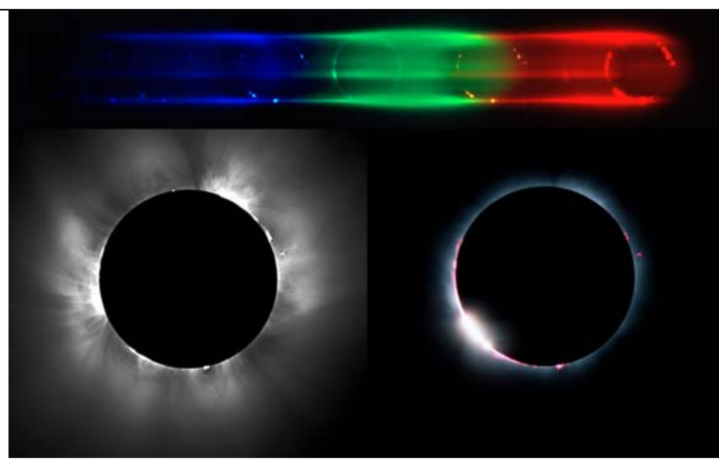


Figure 2.11
The dominant emission lines are the Balmer series from H-alpha to H-delta and the Helium D3 line at 5876A. The two strong coronal lines [FeXIV] 5303 and [FeX] 6374 can be seen with a different spatial distribution. Two images show – one of the red (1/2 sec) and blue (1 sec) exposures taken approximately in mid-eclipse. These are labeled with the hydrogen, helium, iron and calcium lines which are clearly visible. The calcium H and K lines are in a region where the lens focus is not perfect. Note the high prominence to the west (right) seen clearly in Ha and D3. The chromospheric (hydrogen, helium, calcium) and coronal (iron) emission lines have quite different spatial distributions.
http://ecf.hq.eso.org/~rfosbury/home/photography/Eclipse99/csp.html

Spectra shown with a direct image taken at 3rd contact by Philippe Duhoux from a site NW of Munich (right side of image). The prominences and the bright low coronal regions can be easily identified. CCD coronal image (left) taken in France at Vouzier (Champagne-Ardennes) by Cyril Cavadore from ESO and L.Bernasconi and B. Gaillard from Obs. de la Cote d'Azur.



http://ecf.hq.eso.org/~rfosbury/home/photography/Eclipse99/csp_cor_chr.jpg
Direct images from ESO Report about the Solar Eclipse on August 11, 1999
http://www.eso.org/outreach/info-events/eclipse99/report-hq.html

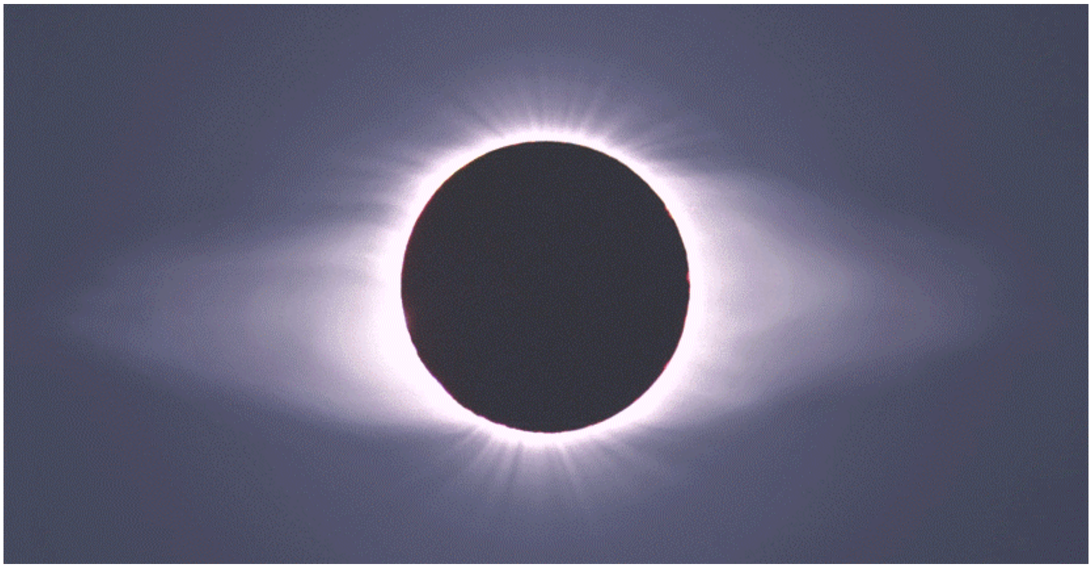


Figure 2.12 This image of the Sun's corona was made from a composite of eight separate photographs made by Fred Espenak from Dundlod, India during the total solar eclipse of 1995 October 24. The photos were made on Kodak Royal Gold 100 with a Nikon FE w/MD-12 motor drive, a Sigma 400mm f/5.6 APO telephoto and a Sigma 2X teleconverter. Exposures were 2, 1, 1/2, 1/4, 1/8, and 1/15 and 1/125 seconds. The eight images were combined into one composite image in order to show the corona properly. Photo ©1996 Wendy Carlos and Fred Espenak.
http://umbra.nascom.nasa.gov/eclipse/images/eclipse_images.html

The best way to see the corona, however is in x-rays. This has been done with film, from skylab, and via electronic means, as with Yohkoh.

Figure 2.13 The corona X-Ray Spectographic Telescope (S054) on Skylab provided some of the earliest glimpses of the corona, including the remarkable "boot of Italy" coronal hole structure which persisted for several solar rotations. Image is formed at 2-32 and 44-54 Å With thanks to the efforts of Dave Batchelor at keeping the data set alive.
http://nssdc.gsfc.nasa.gov/nssdc_news/
march95/06_d_batchelor_0395.html

Further information can be found in A New Sun: The Solar Results From Skylab by John A. Eddy (Publ. by National Aeronautics and Space Administration, Washington D.C., 1979).

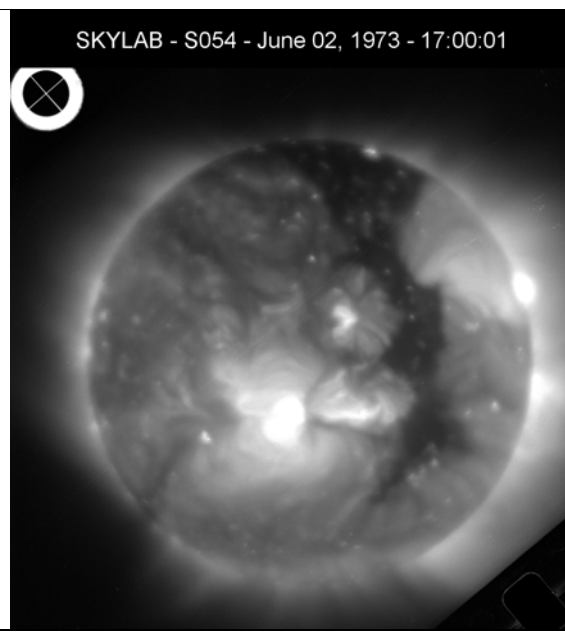
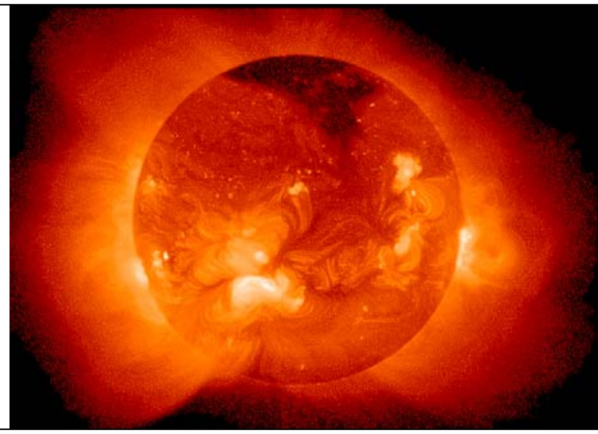
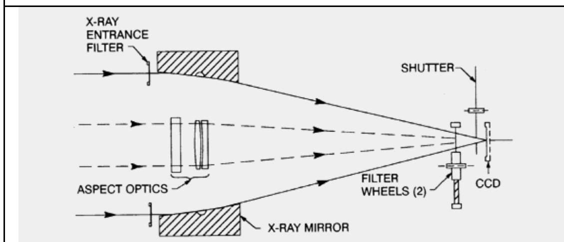


Figure 2.14 This is an X-ray image of the sun taken on 26 August 1992. The image was made up from two pointings of the spacecraft, one to the east and one to the west, to capture the distant corona far above the sun's limb. Again, a coronal hole is obvious at the northern solar pole. (X-ray Filter : AlMg ?) Compare the energy ranges for Yohkoh and skylab	
	The soft X-ray telescope (SXT) is a glancing incidence telescope of 1.54 m focal length which forms X-ray images in the 0.25 to 4.0 keV range on a 1024x1024 virtual phase CCD detector. A selection of thin metallic filters located near the focal plane provides the capability to separate the different X-ray energies for plasma temperature diagnostics. http://www.lmsal.com/SXT/homepage.html

E Solar Magnetism

1 Introduction

The general magnetic field of the sun has intensity of about 100 μT (~ 1 Gauss) at the surface, which is slightly higher than the intensity of the earth's magnetic field (30 - 60 μT). The magnetic field of the sun is largely a surface phenomenon, and the sun's magnetic field should not be thought of in the bar magnet analogy which is so useful for the earth. There is an overall polarity to the sun's field, but it is not steady in time. The most obvious manifestation of the sun's magnetism is in sunspots.

2 Sunspots

Figure 2-15 shows a modern image. Sunspots look like irregular holes in the sun's surface. There is a black inner region, the umbra, with a more luminous fringe, the penumbra. A typical spot is about 10,000 km across, but they have been observed up to 150,000 km. They often occur in pairs (about 90% of the time), and these pairs appear in groups. Sunspots are photospheric regions where the magnetic flux is concentrated and field strengths are on the order of 0.2 to 0.4 Tesla (4000 Gauss). In this region of intense magnetic fields, the temperature, radiation and gas pressure are reduced. The reduced temperature (~ 3900 K) causes the spot to appear darker than the surrounding hotter photospheric gases. (The spot is actually about as bright as the full moon. Observations of sunspots as they approach the solar limb reveals that they are depressions in the surface of the sun.

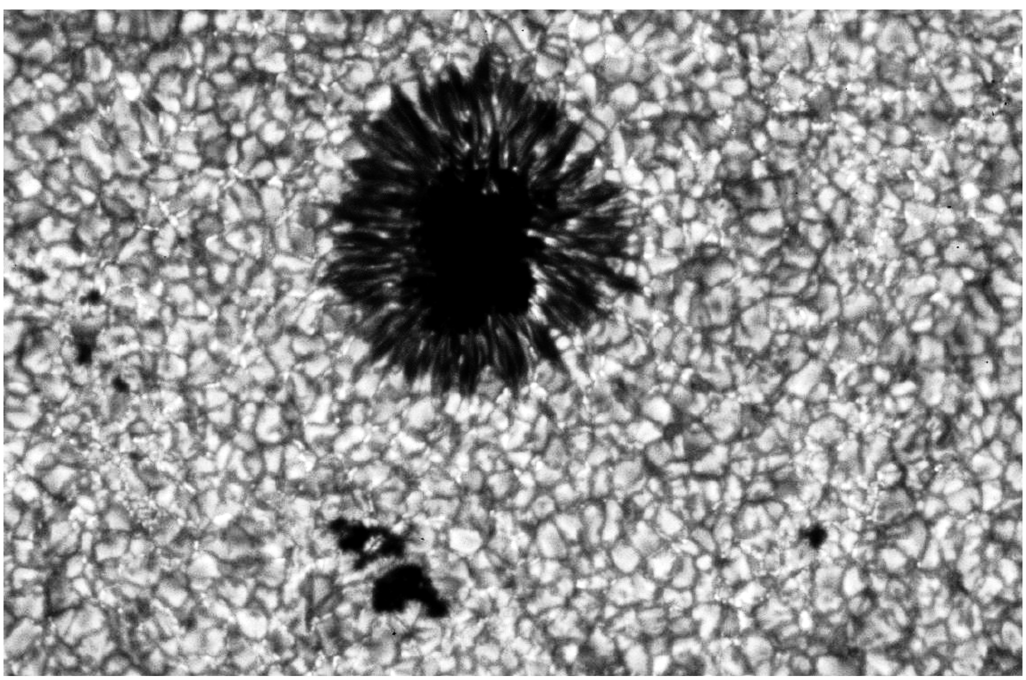


Figure 2.15 White light (continuim) image, 14 June 1994. One sunspot, with a background of granulation. Pores are visible near the bottom of the image. Source: Kiepenheuer/ Uppsala/Lockheed (P. Brandt, G. Simon, G. Scharmer, D. Shine) (Found in WWW).

The magnetic nature of sunspots is revealed in 'magnetograms', measurements of the solar magnetic field obtained from spectral measurements of (polarized) emissions showing the Zeeman Effect - a spectral feature which arises because of the interaction of magnetic fields with the magnetic moments of the electrons. (An excellent discussion of solar magnetism, and the measurement thereof, is given in Our Sun, Menzel, pages 108-117)

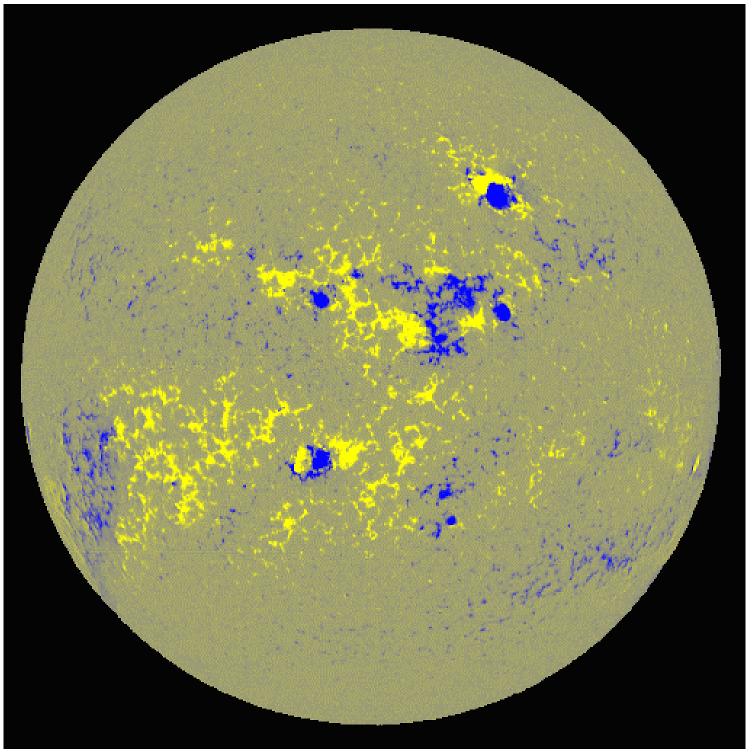


Figure 2.16 Magnetic field measurements, 13 May 1991.

Upon comparing this magnetogram to the Hα or white light images above, one sees that regions of strongest magnetic fields (yellow and light blue on the magnetogram) always coincide with sunspots. Diffuse magnetic fields of lesser strengths are also present all over the solar surface, with moderately strong (Gauss) fields most often associated with plages. Field strengths in sunspots are in the range 1000---4000 Gauss, with the stronger fields in the larger sunspots; this is much larger than the average 0.5 Gauss of the Earth's surface magnetic field. The magnetically active regions also correspond to the hotter regions revealed in the x-ray observations.

Sunspots are almost never seen in complete isolation, but instead are most often grouped in pairs of opposite magnetic polarities. Isolated sunspot pairs tend to line up in the East-West direction (approximately from left to right on this magnetogram). Further scrutiny of magnetograms such as this one reveals that the magnetic polarities of sunspot pairs located in the northern and southern solar hemispheres are reversed; in one hemisphere the negative magnetic polarity sunspot almost always leads the positive polarity sunspot (with respect to the westward apparent motion due to solar rotation), while a similar behavior, except for reversed magnetic polarities, is observed in the other hemisphere.

Individual sunspots may last a few hours to a few weeks. A spot group may persist for several months. It was by following sunspots across the solar surface that the rotational speed of the sun was first determined. Figure 2.17 shows how this velocity varies with latitude. As noted above, the sun does not rotate as a solid body. The rotational period is about 27 days at the equator, as observed from the earth, but rotates more slowly towards the poles.

Most of the interesting solar activity which affects earth-space revolves around magnetic activity which is indicated by sunspots, and the variation in their character. One of the most straight-forward manifestations of this is the sunspot number, which reveals the 11 year solar cycle.

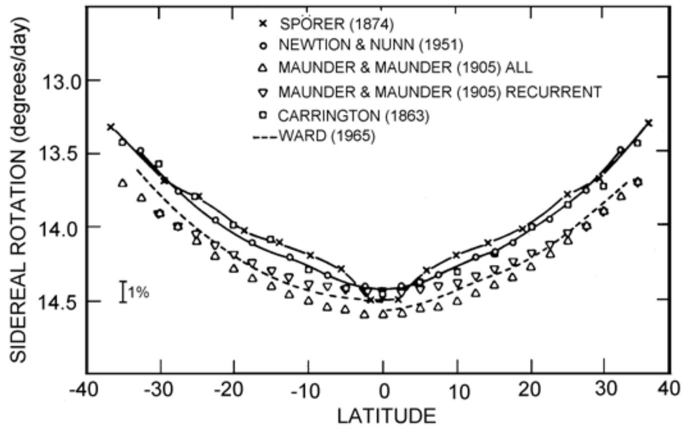


Figure 2.17 Period of the sun's rotation, as determined from sunspots. The results of Newton and Nunn [1951] refer to individual spots. The others refer to spot groups. From: Robert Howard, The Rotation of the Sun, *Reviews of Geophysics and Space Physics, 16,* 721-732, 1978. See also, Robert Howard, the Rotation of the Sun, *Scientific American,* page 106, 19?? (~1978) . (τ ~ 25 days at equator - appears longer from earth)

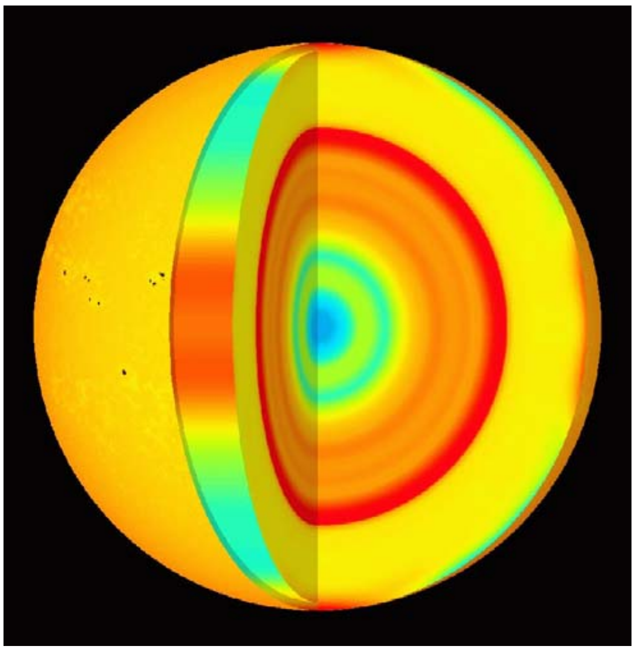


Figure 2.18 Solar rotation and polar flows of the Sun as deduced from measurements by MDI. The cutaway reveals rotation speed inside the Sun. The left side of the image represents the difference in rotation speed between various areas on the Sun. Red-yellow is faster than average and blue is slower than average. The light orange bands are zones that are moving slightly faster than their surroundings. The new SOHO observations indicate that these extend down approximately 20,000 km into the Sun. Sunspots, caused by disturbances in the solar magnetic field, tend to form at the edge of these bands.

3 Sunspot Number and the Solar Cycle

Statistically the sunspot number is closely correlated with many aspects of solar and geophysical activity. Sunspot number as defined below has proven to be a useful index of solar activity. In 1848 Rudolf Wolf in Zürich, Switzerland established the following index to characterize the "spottiness" on the solar surface:

$R = h(10g + s)$

where R = Wolf or Zürich sunspot number
g = Number of sunspot groups (2 or more)
s = Number of individual sun spots
h = Subjective correction factor (Fudge factor) depending on instrumentation and observer.

A plot of monthly averaged sunspot numbers is shown in Fig 2.18 in which several features are apparent.

There is a period of about 11 years between consecutive maxima, but the cycle is not completely regular and varies in period from 8 to 15 years.

The rise time is about 4.8 years and decline is about 6.2 years.
The amplitude of the maximum can vary by almost a factor of 3. The largest annual mean number (190.2) occurred in 1957.

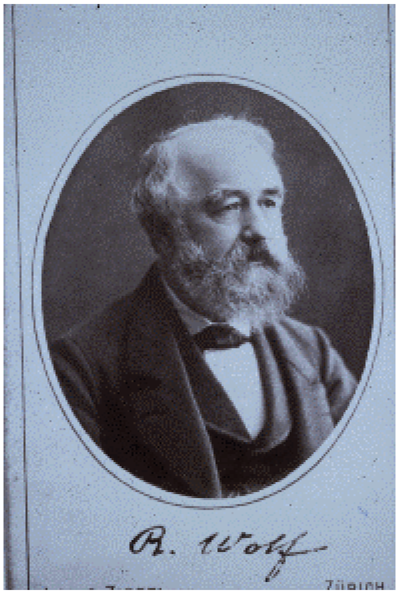


Figure 2.19a Johann Rudolph Wolf (1816-1893).

National Portrait Gallery, Smithsonian Institution, Washington D.C.

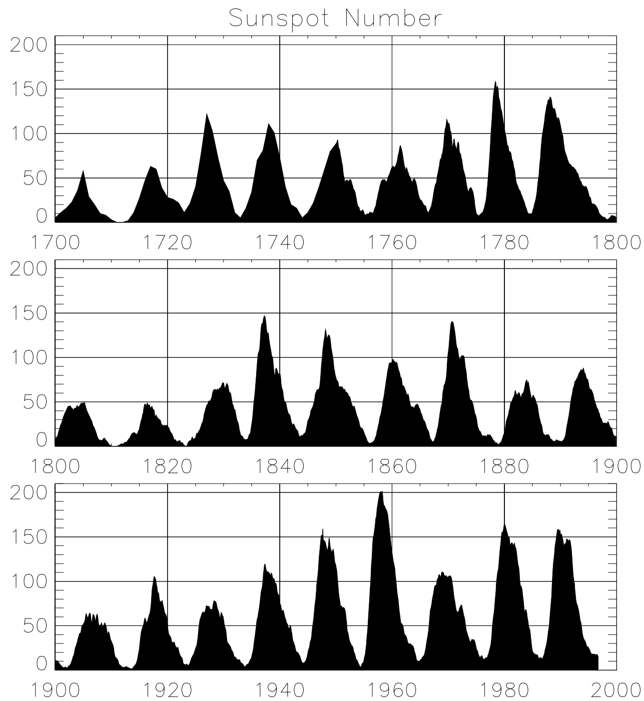


Figure 2.19b Monthly values for sunspot number. (Annual values used 1700-1750).

In 1848 Rudolph Wolf devised a daily method of estimating solar activity by counting the number of individual spots and groups of spots on the face of the sun. Wolf chose to compute his sunspot number by adding 10 times the number of groups to the total count of individual spots, because neither quantity alone completely captured the level of activity. Today, Wolf sunspot counts continue, since no other index of the sun's activity reaches into the past as far and as continuously. An avid astronomical historian and an unrivaled expert on sunspot lore, Wolf confirmed the existence of a cycle in sunspot numbers. He also more accurately determined the cycle's length to be 11.1 years by using early historical records. Wolf, who became director of the Zurich Observatory, discovered independently the coincidence of the sunspot cycle with disturbances in the earth's magnetic field.
http://web.ngdc.noaa.gov/stp/SOLAR/SSN/ssn.html

The latitudes where sunspots are formed changes in a systematic way during the 11 year cycle. At the start of a cycle (minimum) the spots tend to form near $\pm 35°$ solar latitude. As the cycle progresses they form at successively lower latitudes as shown in Figure 2.20 down to about ±5° just as the next cycle begins at the higher latitudes. There is about a 2 year overlap between successive cycles when both high and low latitude spots appear.

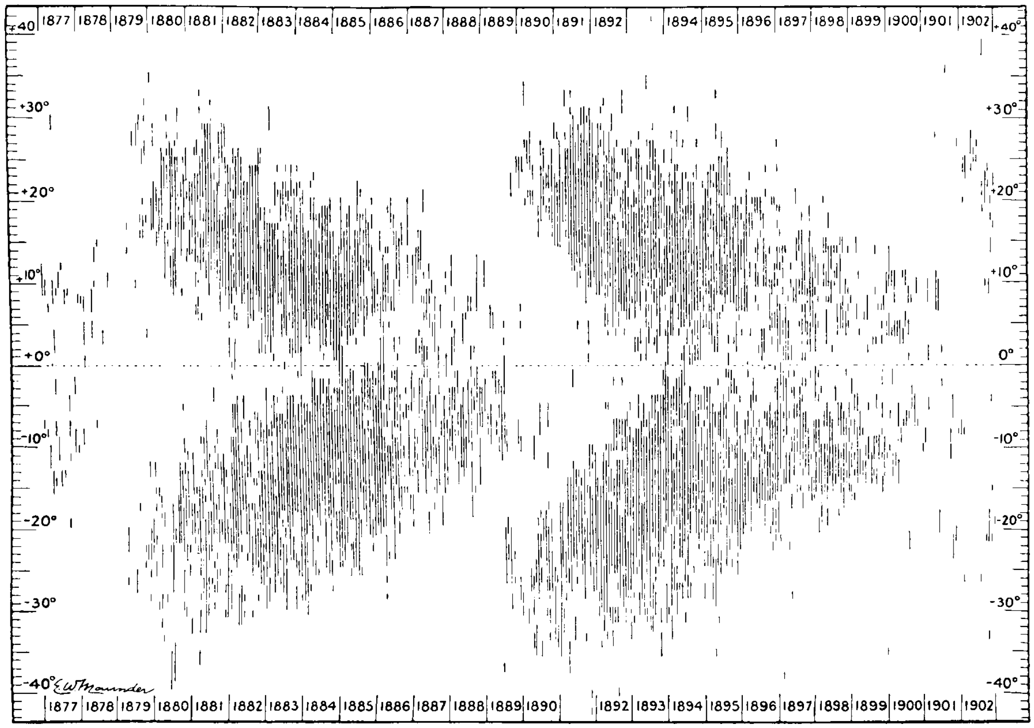


Figure 2.20 The Maunder "butterfly" diagram showing variation in distribution of sunspots with time. During a sunspot cycle the distribution migrates toward the solar equator. From: E. W. Maunder, "Notes on the Distribution of Sun-Spots in Heliographic Latitude, 1874-1902," *Royal Astronomical Society Monthly Notices*, volume 64, pages 747-761, 1904. (Found in the book by Edward Tufte, Envisioning Information, Graphics Press, Cheshire, CT., 1990). The vertical strips reflect the latitudinal range of a given measurement. For a modern version, see http://wwwssl.msfc.nasa.gov/ssl/pad/solar/sunspots.htm, and the butterfly diagram by David Hathaway at NASA/MSFC -http://wwwssl.msfc.nasa.gov/ ssl/pad/solar/images/bfly.gif

For any given cycle the leader spot in any given group normally has the polarity of the nearer pole at the beginning of the cycle (minimum). The orientation of polarity remains unchanged during any given cycle. However, shortly after solar maximum the polarity of the large scale magnetic field weakens and reverses. When the next cycle starts (at solar minimum) spots formed at high latitudes will have the opposite polarity orientation compared to the old, low latitude spots belonging to the previous cycle. Thus the time required to return to the original magnetic configuration is about 22 years. For this reason, a complete solar cycle is typically considered to be 22 years, not 11 years.

The cause for much of this activity appears to have it's source in the differential rotation of the sun's surface. As noted above, the sun does not rotate as a solid body. On earth the angular rotation rate is 360° per day regardless of latitude. On the sun the angular rotation rate at the equator is about 30% faster than at the poles. The rotation rate at the equator is about 13°/day on the equator and about 10°/day near the poles. As viewed from the earth, the sun's rotational period is generally considered to be ~27 days, and most solar related effects observed at earth show variations with this period. The general magnetic field is "frozen into" the surface due to the high plasma density. In the photosphere and below the kinetic energy density is much higher than the field energy density and hence the plasma motion determines the shape of the field.

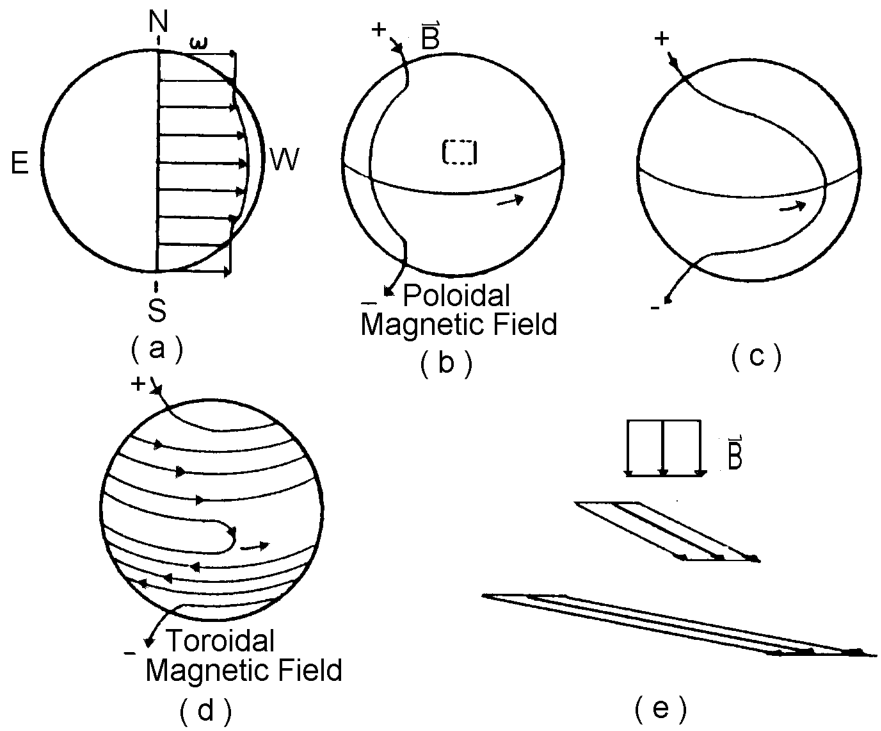


Figure 2.21. Enhancement of surface solar magnetic fields by differential rotation. (a) The general variation of angular velocity with latitude. Starting with a frozen-in longitudinal magnetic fields as shown in (b), differential rotation will wind it up as shown in (c) and (d). (e) The effect on the surface fluid element denoted in (b). The field lines are moved closer together under the shearing action of differential rotation and the field strength is thereby increased. (b to d are after Livingston, 1966. Gibson, 1972]

The differential rotation winds up the general magnetic field lines which initially lie in planes through the axis of rotation (a poloidal field). As this process proceeds, the field lines are eventually wrapped around the axis of rotation (a toroidal field) and the strength of the field is greatly increased as a result, as shown in Figure 2.21.

Convective motions below the photosphere further increase the density of the field lines twisting the tubes of enhanced flux into rope like structures (Figure 2.22 a). Kinks in these ropes of flux caused by small scale turbulence can produce even greater field strength within small local regions. When field strength (and hence the magnetic pressure) become large enough the flux tube can become buoyant and wells up through the surface. The regions where the tube penetrates the photosphere are known as sunspots and the field above fan out into a loop configuration with preceding (p) and following (f) spots of opposite polarity as shown in Fig (2.22 b).

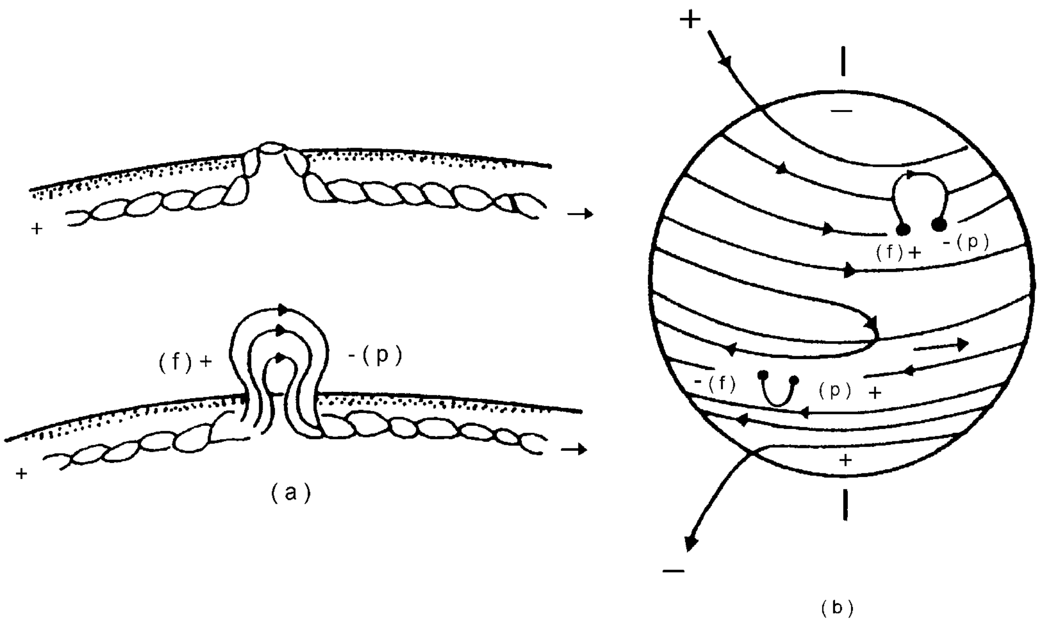


Figure 2.22 Formation of the bipolar sunspot magnetic field configuration. (a) Enhanced flux lines twisted by convective motion below the photosphere. (b) Spools formed by buoyant magnetic field (Gibson, 1972).

F Solar Activity

1 Prominences

Although the total energy output of the sun appears to be very stable there are a great variety of local disturbances discernible on the solar disk. In these so called "Active Regions" significant fluctuations in density, temperature and energy output can occur for periods lasting from minutes to weeks. The solar surface is a very turbulent place and many types of instabilities have been identified and should be studied in the photosphere, the chromosphere and the corona. The two examples of such behavior we will consider are prominences and solar flares.

Prominences, as illustrated in Figures 2.23 and 2.24, are extrusions of 'cold' chromospheric gas up into the corona, extending up out of active regions of enhanced magnetic field strength. They often show a loop like structure, as in the illustration, indicating that the plasma is confined by a loop like magnetic field structure, like that shown in Figure 2.23. When viewed against the sun's surface, they appear dark, since they are cooler than the background photosphere. Under these conditions, they acquire the name 'filament', but they are the same physical feature. Prominences are relatively long lived, often lasting many days. They are carefully watched by solar observers, as they often evolve into solar flares.

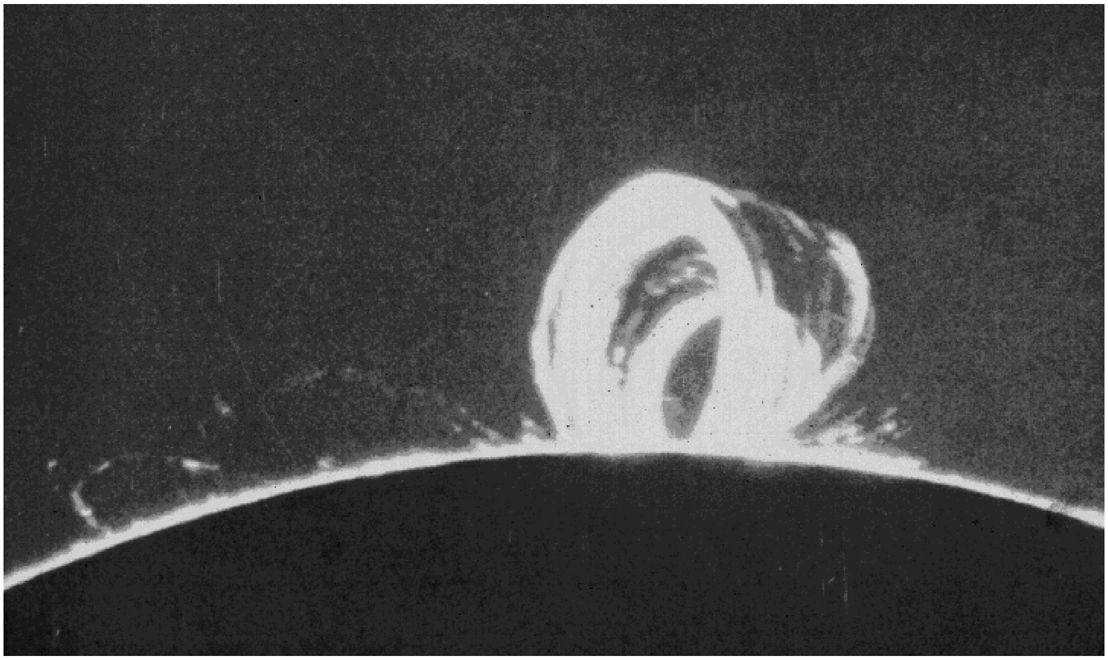


Figure 2.23 Loop Prominences, photographed in H-alpha. The image was taken circa June or July 28, 1957, taken at Sacramento Peak Observatory by Dr. Richard Dunn, a graduate student at that time. (http://www.sunspot.noao.edu/gifs/loops.gif) Since then, the (solar) Vacuum Tower Telescope he later created (1969) at the National Solar Observatory at Sacramento Peak, New Mexico was renamed as the Richard B. Dunn Solar Telescope. (1998)

Eruptive prominences, such as the one illustrated in Figure 2.24 can produce major disturbances in the corona, and solar wind (chapter 3). These structures emerge over a period of 1-2 hours. Still, the most significant changes in the near earth satellite environment come from solar flares. Solar flares emerge from magnetically active regions, typically where prominences and sunspot groups are also found. When these "kinks" in the field relax and the field lines begin to return to their original shape large amounts of magnetic energy become available in fairly small regions which turn "active" as a result.

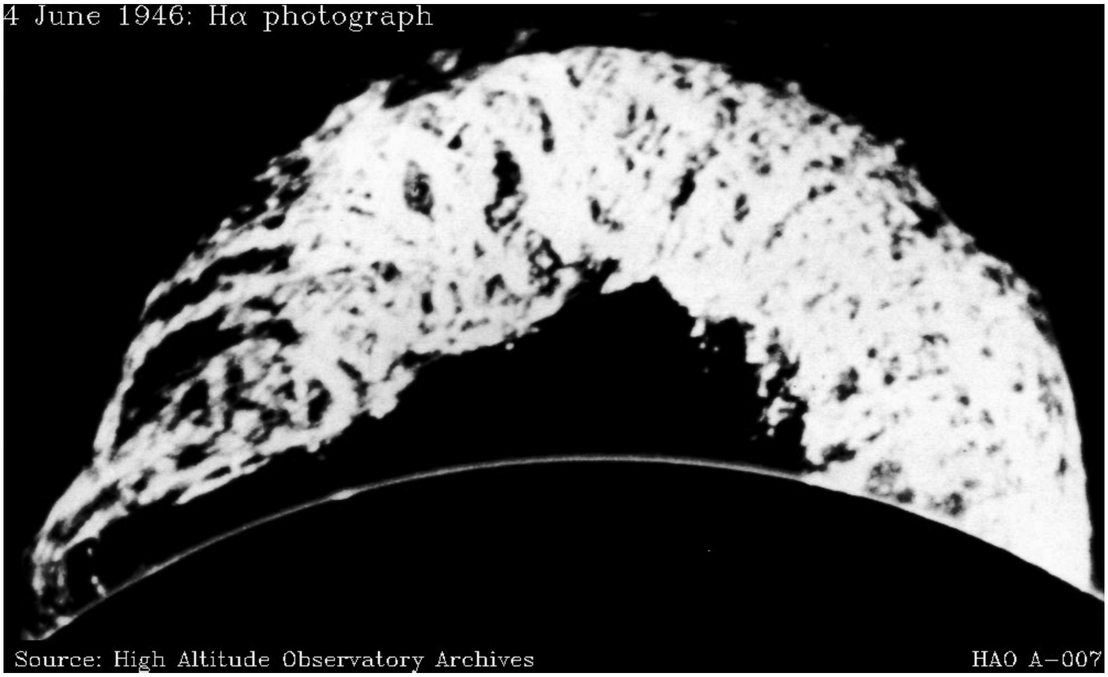


Figure 2.24 This solar eruption, an eruptive prominence, occurred on 4 June 1946, and is one of the largest ever recorded. It developed in 2 hours, reaching an altitude of nearly 1 million miles before disappearing.
From: The McGraw-Hill Encyclopedia of Space, page 506, 1968. Found on WWW, courtesy Paul Charbonneau, HAO. The progression of this famous prominence is found in: The Solar Atmosphere, Harold Zirin; The Sun, Our Star, Robert Noyes; Our Sun, Donald Menzel, and A Star Called the Sun, George Gamow.

2 Solar Flares

Prominences, as illustrated above, are dramatic but relatively common solar features. They consist of chromospheric plasma, that is plasma with a characteristic temperature of 4000-5000 degrees. (It is the fact that the contents of the prominence are cooler than the background solar surface which cause them to appear as dark filaments against the sun. They are only perceived as being bright in comparison to the tenuous corona). Solar flares, by contrast, are much less common, and very hot. These plasmas differ from those found in prominences, in that they are much more energetic. Viewed against the background of the sun, they are bright regions. They have even been observed by 'naked' eye observers, with a report by Carrington and Hodgson dated Sept 1, 1859 being one of the first such reports. They duly noted subsequent magnetic activity at earth, beginning the idea that there was a relationship between solar activity and earthly activities. (Phillips, Guide to the Sun, page 32) Figure 2.25 shows the famous "sea-horse" flare, which resulted in one of the largest magnetic storms observed during the space age. It resembles the prominence in shape, again reflecting the strong effect of the magnetic field structure on the plasma behavior.

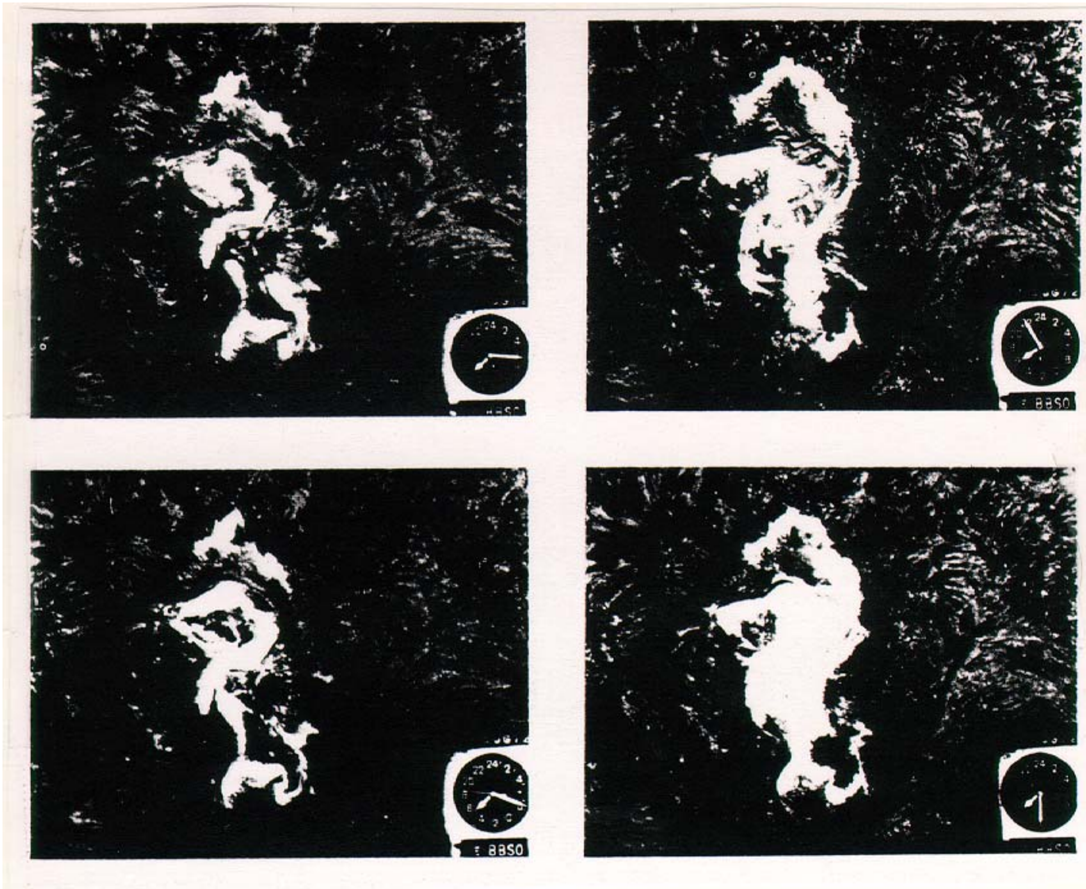


Figure 2.25 The development of a solar flare on 7 August 1972 is shown in sequence, in images taken at Big Bear Solar Observatory (BBSO). The progression starts at 1515, in the top left. The flare has visibly brightened by 1520 (bottom left), and has reached it's peak brightness by 1530 (bottom right). By 1550 (top right), the flare has noticably decayed. From: Cambridge Encyclopedia of Astronomy, edited by Simon Mitton, page 149, 1977.

Radiation of all frequencies from radio to x-rays as well as pulses of high energy particles (electrons, protons and some alpha particles) are emitted in a typical flare. Flares are monitored by the NOAA/GOES platforms, and watched for in x-rays and energetic particles (solar protons). Figure 2.26 shows data from a more sophisticated instrument on the Solar Maximum Mission, which observed X-rays. Figure 2.26 shows the 24-48 keV (~0.5-0.25 Å) channel for 4 flares. The largest fortuitously came immediately after the SOLAR MAX rescue mission, on 24 April 1984. Notice the abrupt rise in flux, over a period of less than a minute. Energetic particles will start reaching the earth some hours later, and the plasma (shock wave) in the solar wind, several days later. The x-ray, and extreme ultraviolet (UV) flux has immediate effects on the upper atmosphere, heating it, and ultimately causing low altitude satellites to experience increased drag (Chapter 6). Note that the x-ray flux from one flare is greater than the x-ray production of the 'quiet' sun, integrated over the entire solar surface. High altitude satellites are more directly influenced by the solar wind shock wave arriving a few days later, while the energetic protons are primarily a problem for humans in space, but can lead to the degradation of electronics..

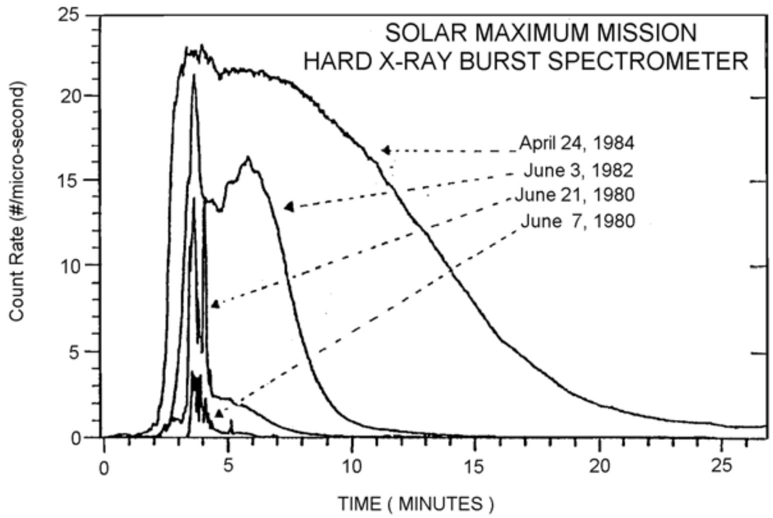


Figure 2.26 The development of 4 solar flares in hard x-rays. Figure from Dr. Alan Kiplinger, NASA/GSFC, March 1988.

While the visible emission from a flare increases by at most a few percent, x-ray emissions may increase as much as four orders of magnitude as measured by satellites above the earth's atmosphere (e.g. Figure 2.26). Measurements are made in several x-ray bands and flares are also classified according to the peak energy flux of the core. The increase in UV and higher energy photons is important for the degree of ionization of the ionosphere, and atmospheric heating as noted above. Also, it is relatively easy for geosynchronous weather satellites (e.g. GOES) to monitor solar activity via x-rays.

Flares are classified according to their size and intensity. The size or "importance" is based on flare area measured in millionths of solar disk area, and in the Doppler shift found in the H-alpha observations (e.g. the velocities). Duration is also directly related to the "importance". The total energy released during a flare may range from 10^{21} to 10^{25} Joules integrated over the three phases (1) precursor (or preflare) phase (2) flash and (3) main (or gradual) phase. The mean duration of a flare is roughly correlated to its magnitude (or importance)

IMPORTANCE	AVERAGE DURATION	PERCENT OF ALL FLARES
0	17 minutes	75
1	32 minutes	19
2	69 minutes	5
3 and 4	more than 2 hours	less than 1

Various models of solar flares have been proposed, but none explains all the flare observations. It is currently believed that the solar flare energy is probably stored in the twisted and kinked magnetic field lines above the active solar regions. By some triggering mechanism either within the field itself or from the outside the geometry of the field lines is rearranged and a portion of the stored energy is released. During this process large electric fields are generated which accelerate charged particles both outward and downward into the denser layers of the sun. It is estimated that between 10^{33} and 10^{36} electrons are accelerated to an average energy of 25 keV each second. These large fluxes of charged particles in turn are responsible for high levels of electromagnetic radiation emitted by the flare. Some fraction of the charged particles escape outward and eventually reach the earth where they are responsible for a number of effects which will be discussed in subsequent chapters.

There is an approximate empirical relationship between the number of flares per day and the sunspot number R defined above:
number of flares/day ~ R/25

which means one flare every few days at solar min when R is 5 - 10 and a maximum of several flares per day at solar max when R is 100 - 150, typically.

3 Coronal Mass Ejections

Coronal Mass Ejections (CME's) have conventionally been thought of as a manifestation of solar flares - that is a response in the upper solar atmosphere to the explosion occurring near the solar surface. There is now, however, a fairly vigorous debate in the solar-terrestrial community as to the causes of CME's, instigated to a certain extent by Jack Gosling, a researcher at Los Alamos National Laboratory. (See discussion in EOS, (Transactions of the American Geophysical Union), vol. 76, #41, page 401, 10 October 1995) The significance of the problem is that CME's are a major factor in magnetic storms on earth. Hence, understanding their origins is essential to understanding the causes of magnetic storms on earth.

They have been regularly monitored in recent times from ground based coronagraph instruments. Figure 2.27 shows further measurements from the satellite borne coronagraph on SMM, and a particularly well ordered mass ejection. Here, up to 10^{13} kg of coronal material may be ejected outwards at speeds as high as 1000 kilometers/second. In this case, a 'helmet streamer', as shown in the frame at 10:04, had been visible for a few days, during which time it showed little change in shape or brightness. An erupting prominence can be seen to form, and there may be material from the prominence visible in the bright filaments found at 13:10.

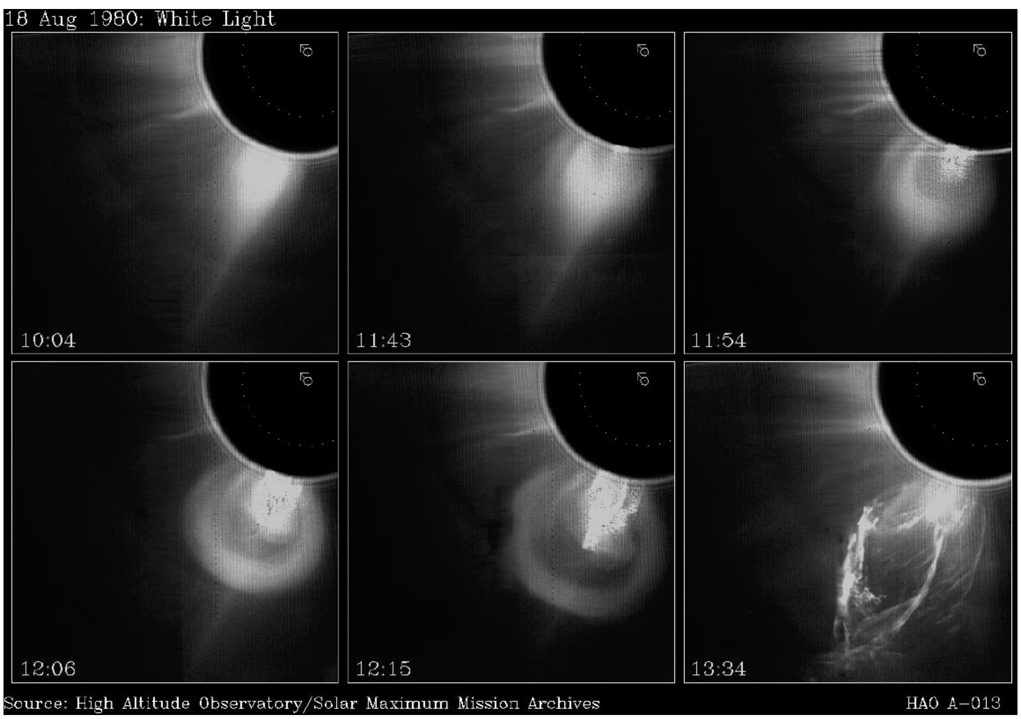


Figure 2.27 Coronal mass ejection, as observed by SMM, 18 August 1980. WWW, HAO, Charbonneau and White.

G Energy Production in the Sun

It is generally agreed that in the core of the sun ($r \leq 0.2\ R_\odot$) energy is generated by the fusion of protons into He nuclei. The conditions for this self-sustaining reaction are brought about by the gravitational contraction of the sun which will compress and heat the core until thermonuclear ignition takes place.

Present calculations indicate that conditions in the core are

Density $\approx 10^5$ kg/m^3 (about 100 times water density on earth)
Temperature $\approx 1.5 \times 10^7$ K (corresponds to an average energy of about 1 keV)
Pressure $\approx 2.5 \times 10^{11}$ atmospheres $\approx 2.5 \times 10^{16}$ (N/m^2)

There exist two major reaction cycles which convert atomic hydrogen nuclei into helium nuclei by thermonuclear fusion. In this process a small fraction of the mass of the system is converted into energy according to Einstein's equation

$$\Delta E = \Delta mc^2$$

where c = velocity of light = 3×10^8 (m/s)

$$\Delta m = 4(\text{proton masses}) - (\text{He})\text{ mass}$$

The loss of mass is about 0.7% of the original proton masses which means that about 4×10^{-12} J (25 MeV) of energy are generated per helium nucleus formed.

If the core temperature is actually about 15 million K most of the energy is generated by the so called proton-proton cycle

$$\left\{\begin{array}{l} p + p \to d + e^+ + \nu_e \\ p + d \to {}^3\text{He} + \gamma \\ 2\ {}^3\text{He} \to {}^4\text{He} + 2p \end{array}\right\}$$

d = deuteron
e^+ = positron
γ = Gamma ray
ν_e = neutrino

At slightly higher temperatures another cycle begins to function. This so-called CNO cycle goes something like this:

$$\left\{\begin{array}{l} {}^{12}\text{C} + p \to {}^{13}\text{N} + \gamma \\ {}^{13}\text{N} \to {}^{13}\text{C} + e^+ + \nu_e \\ {}^{13}\text{C} + p \to {}^{14}\text{N} + \gamma \\ {}^{14}\text{N} + p \to {}^{15}\text{O} + \gamma \\ {}^{15}\text{O} \to {}^{15}\text{N} + e^+ + \nu_e \\ {}^{15}\text{N} + p \to {}^{12}\text{C} + {}^4\text{He} \end{array}\right\} \quad \text{CNO Cycle}$$

Note that in both of these cycles the net transformation is $4p \Rightarrow {}^4He$ plus energy and light particles such as e^+, ν_e. Since neutrinos interact only very slightly with matter they will generally leave the sun carrying a certain amount of energy with them. For this reason the actual energy made available to the star is somewhat different for the two cycles.

Proton - Proton Cycle: 26.71 MeV/He nucleus formed

CNO Cycle: 25.03 MeV/He nucleus formed

Where 1 MeV = 10^6 eV = 1.6×10^{-13} Joules. At the present rate of energy production the sun burns 6×10^{11} kg of hydrogen per second.

The extreme pressures and temperatures in the core of the sun are necessary to sustain these reactions for 2 reasons: (1) The particles must hit "hard enough" for the reactions to occur (high temperature) and (2) They have to hit often enough so that the energy emitted is high enough for the reaction to continue. Thus both high temperatures and high densities are essential. Finally we must have sufficient inward gravitational attraction to hold the whole thing together. Amazing!

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I Problems

1. The temperature in the photosphere varies from 4400-6400 K. Calculate how the spectral peak varies in wavelength for the different regions (Wien's displacement law), and how the emitted power varies (Stefan-Boltzmann law).

2. During a solar eclipse we can see part of the solar atmosphere. Which part do we see and why?

3. Show that the photospheric pressure is only one percent of the earth's surface atmospheric pressure. Take the sun's surface gravitational field to be 30 times as great as on earth and the total mass of the solar atmosphere to be about 2.1 x 10^{19} kg compared to 5.29 x 10^{18} kg for the earth's atmospheric mass.

4. Assume that the average sunspot field is 0.3 Tesla within a volume of $(10^4 \text{ km})^3$. Compute the **percentage** decrease in stored magnetic energy needed to produce a flare with energy of 10^{25} Joules.

5. Plot n_e vs r for the corona, assuming a barometric relationship. The appropriate formula to use is:

$$n_e = n_o \exp\left[\frac{G M_\circ \mu m_H}{kT R_\circ}\left(\frac{1}{r} - \frac{1}{r_o}\right)\right]$$

(From: *Astrophysical Formula,* Kenneth R Lang, Springer-Verlag, p 286, 1974.) Note that in this equation, the r and r_o terms are in units of solar radii (e.g. 1, 2, 3...). μ is the effective mean molecular weight, which is ≈ 0.8 in the sun's atmosphere, taking into account the protons, alpha particles, and electrons. All the <u>other</u> numbers should be done in mks. Try temperatures of 1.0, 1.5, and 2.0 million K. Begin with $n_e \approx 3 \times 10^{14}\ \text{m}^{-3}$ at $r = r_o = 1$, and assume $n_e \approx 3 \times 10^{10}\ \text{m}^{-3}$ at $r = 5$. What temperature produces the best result ? Note that the barometric relation breaks down fairly quickly, but it produces one indirect indication of the temperatures which must exist in the stellar atmosphere.

6. The sun generates energy at the rate 4 x 10^{33} erg/sec by the conversion of hydrogen to helium. Show that if hydrogen could be completely converted to energy, it would require over 4 million metric tons of hydrogen to produce the observed solar energy generation rate. Assume that the energy conversion reaction is simply: $4H_1^1 \rightarrow He_2^4 + 2e^+ + \text{energy}$, where e+ are positrons and the energy liberated per reaction is 25 MeV. (The energy comes off primarily in the form of neutrinos) Show that the sun would need to convert 6.68 x 10^{11} kg of hydrogen into 6.64 x 10^{11} kg of helium per second to produce the observed energy generation rate. (The mass defect for the energy conversion reaction is 0.0266 AMU).

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